

# Guidelines for more accurate determination and interpretation of effective lifetime from measured quasi-steady-state photoconductance

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This paper clarifies three measures that should be taken to more accurately calculate and interpret the effective lifetime ( $\tau_{\text{eff}}$ ) from quasi-steady-state photoconductance: 1) In order to account for the dependence of photogeneration on the illuminating spectrum and the test wafer reflectance, the correct value is assigned to the effective optical transmission. 2) In order to account for the dependence on the illuminating spectrum of the constant of proportionality between the short-circuit current of the reference cell and the total photon flux, we introduce a spectral correction factor. 3) Once the correct value of  $\tau_{\text{eff}}$  has thus been found, the solution to the time-dependent continuity equation is applied to assess the error in the commonly used expression  $1/\tau_{\text{eff}} = 1/\tau_b + 2S/W$ , relating  $\tau_{\text{eff}}$ , bulk lifetime ( $\tau_b$ ), and surface recombination velocity ( $S$ ). An example illustrates that ignoring these three guidelines can cause  $S$  to be underestimated by over 40%.

## 1. Introduction

The quasi-steady-state photoconductance (QSSPC) technique is very effective for determining the minority-carrier lifetime of photovoltaic-grade multicrystalline silicon materials [1, 2]. In the analysis of a quasi-steady-state photoconductance (QSSPC) measurement, in which the time-derivative of the average excess carrier concentration ( $n_{\text{av}}$ ) is negligible, the effective lifetime ( $\tau_{\text{eff}}$ ) is inversely proportional to the average generation rate ( $G_{\text{av}}$ ) in the test wafer [3]:

$$\tau_{\text{eff}}(n_{\text{av}}) = \frac{n_{\text{av}}(t)}{G_{\text{av}}(t) - \frac{dn_{\text{av}}(t)}{dt}}. \quad (1)$$

Thus in order to calculate  $\tau_{\text{eff}}$  accurately,  $G_{\text{av}}$  must be correctly computed from the measured short-circuit current of the reference solar cell. We illustrate this procedure by referring to the commonly used Sinton data analysis spreadsheet [4], in which  $G_{\text{av}}$  is proportional to the value assigned to the effective optical transmission (EOT):

$$G_{\text{av}} = \text{Suns} \times \text{EOT} \times (38 \text{ mA/cm}^2) / (q \times W), \quad (2)$$

where  $q$  is the electronic charge,  $W$  is the wafer thickness, and (EOT) must be correctly adjusted from 1 according to the deviation of the generation current from  $38 \text{ mA/cm}^2$  [4]. While an illustration of the dependence of EOT on wafer thickness and surface coating can be found [4], a description of the calculation of EOT does not appear to exist in the literature. Another point worthy of clarification is the interaction between the spectral response of the reference cell and the spectrum of illumination. Since the constant of proportionality between the short-circuit current ( $J_{\text{sc}}$ ) of the reference cell and  $G_{\text{av}}$  depends on the spectrum of illumination [5], we introduce a spectral correction factor (SCF) to generalize the standard data analysis for arbitrary spectra. While improper assessment of EOT and SCF introduces error in the calculation of  $\tau_{\text{eff}}$ , the subsequent use of the following approximate equation can introduce error in the calculation of  $\tau_b$  or  $S$ , assuming one of the two is known:

$$\frac{1}{\tau_{\text{eff}}} = \frac{1}{\tau_b} + \frac{2S}{W}. \quad (3)$$

The accuracy of Eq. (3) should be evaluated by comparison with the solution to the continuity equation for exponentially decaying illumination intensity, discussed elsewhere [6]. In order to describe the accurate calculation and interpretation of  $\tau_{\text{eff}}$ , this paper elucidates the theoretical determination of EOT and SCF, applies the solution of the continuity equation to evaluate the accuracy of Eq. (3), and uses measured data to illustrate the importance of these steps to the computation of  $\tau_{\text{eff}}$ .

## 2. Theoretical calculation of effective optical transmission

Defining  $N_{\text{abs}}(\lambda)$  as the incident photon flux spectral density *that gets absorbed in the wafer*, and assuming that each photon absorbed generates one electron-hole pair, then Eq. (2) can be rewritten as

$$EOT = \frac{\int N_{\text{abs}}(\lambda) d\lambda}{\text{Suns} \times (38 \text{ mA/cm}^2) / q}. \quad (4)$$

Suns can be written as the ratio of the incident photon flux  $N_{\text{ph}}$  to the photon flux in 1 Sun, which from 300 nm to 1200 nm is  $(46.9 \text{ mA/cm}^2)/q$ :

$$EOT = \frac{46.9}{38} \times \frac{\int N_{\text{abs}}(\lambda) d\lambda}{\int N_{\text{ph}}(\lambda) d\lambda}. \quad (5)$$

In order to find  $N_{\text{abs}}(\lambda)$  as a function of  $N_{\text{ph}}(\lambda)$ , we integrate the generation rate [7] to obtain

$$N_{\text{abs}}(\lambda) = \frac{N_{\text{ph}}(\lambda)[1 - R(\lambda)][1 + R(\lambda)e^{-\alpha(\lambda)W}](1 - e^{-\alpha(\lambda)W})}{1 - [R(\lambda)e^{-\alpha(\lambda)W}]^2}. \quad (6)$$

Equation (8) neglects any reflection off the surface the wafer is resting on. Using Eqs. (5) and (6), EOT can be calculated for any wafer whose  $R(\lambda)$  and  $W$  are known, given that  $N_{\text{ph}}(\lambda)$ , the photon flux spectral density of the lamp, is also known.

## 3. Spectral correction factor for the calculation of $\tau_{\text{eff}}$ under arbitrary illumination spectra

Experimentally, the value of Suns in Eq. (2) is found by its proportionality with the voltage (V) across a small resistor (R) through which  $J_{\text{sc}}$  of the reference solar cell flows. Assuming illumination with the AM1.5 spectral content, it can be shown that

$$\text{Suns} = \left( qAR \times \int n_{\text{AM1.5}}(\lambda) EQE(\lambda) d\lambda \right)^{-1} V, \quad (7)$$

where  $n_{\text{AM1.5}}(\lambda)$  is the photon flux spectral density of 1 Sun, AM1.5; EQE is the external quantum efficiency of the reference cell; and the factor in parentheses is provided in the spreadsheet as the V/Sun factor. This factor is assumed to have been obtained empirically under 1 Sun, approximately AM1.5 illumination. Note that Eq. (7) is accurate only under AM1.5 illumination. Under an arbitrary spectrum of illumination,  $n_{\text{AM1.5}}$  must be replaced by  $n_{\text{spec}}$ , the photon flux spectral density of the illuminating spectrum, normalized to 1 Sun intensity. Thus we define the spectral correction factor as

$$SCF = \frac{\int n_{\text{AM1.5}}(\lambda) EQE(\lambda) d\lambda}{\int n_{\text{spec}}(\lambda) EQE(\lambda) d\lambda}, \quad (8)$$

so that Eq. (7) can be correctly generalized for illumination by an arbitrary spectrum as

$$Suns = SCF \times \left( qAR \times \int n_{AM1.5}(\lambda) EQE(\lambda) d\lambda \right)^{-1} V, \quad (9)$$

where Suns is taken to indicate the factor by which the total incident photon flux differs from that of 1 Sun, regardless of the incident spectrum. Thus, we multiply by SCF so that the V/Sun factor, in parentheses in Eq. (9), can be left unmodified. At last, define the modified spectral correction factor  $SCF' = SCF \times EOT$  so that Eq. (2) can be revised to

$$G_{av} = SCF' \times Suns \times (38 \text{ mA/cm}^2) / (q \times W). \quad (10)$$

Thus, EOT is replaced by  $SCF'$  in the data analysis spreadsheet to account for spectral effects.

Equation (8) is used to calculate SCF for the white light of the Quantum Qflash T2 lamp, whose spectral irradiance was measured at NREL. We use the EQE of a cell measured at ISE; the reference cell in our laboratory, though from the same manufacturer, is expected to behave similarly though not identically. Equation (8) gives  $SCF = 0.913$  for the full spectrum of the flash lamp shining through two diffuser plates; this value depends only on the illuminating spectrum and is independent of the test wafer. Figure 1 shows that the use of SCF improves the strongly predicted agreement between transient and QSSPC lifetime data for a wafer with  $S < 50 \text{ cm/s}$  [8]. In all cases, we use the calculated  $EOT = 1.08$  for this nitride-coated wafer.

EOT is computed from Eqs. (5) and (6) as a function of wafer thickness using the measured reflectance of three common surface coatings.  $SCF' = SCF \times EOT$  is plotted in Fig. 2. We recommend that in accordance with Eq. (10), the calculated  $SCF'$  be used in place of EOT in the data analysis spreadsheet. Assuming that the reflectance curves on which Fig. 2 is based are typical of the specified anti-reflection coatings,  $SCF'$  can be read from the figure for use in data analysis.

#### 4. Comparison of $1/\tau_{eff} = 1/\tau_b + 2S/W$ with solution to time-dependent continuity equation

Assuming  $\tau_{eff}$  is measured and  $\tau_b$  is known, the error in  $S$  resulting from the use of Eq. (3) in QSSPC is obtained by comparison with the solution to the time-dependent continuity equation. Figure 3 shows that Eq. (3) underestimates  $S$  by more than 25% when  $S > 10000 \text{ cm/s}$ , for a  $300 \mu\text{m}$  wafer. Thus, once  $\tau_{eff}$  is obtained by correctly accounting for photon absorption and spectral response through EOT and SCF, care must be taken to use Eq. (3) only when justified by the solution to the continuity equation [6].

#### 5. Effects of ignoring EOT, SCF, and continuity equation on lifetime data analysis

To illustrate the importance of EOT, SCF, and the use of the full solution to the continuity equation in place of Eq. (3) for high  $S$ , we take the example of a heat-exchanger method (HEM) multicrystalline silicon wafer coated with  $\text{SiN}_x$ . Assume knowledge of  $\tau_b = 48.3 \mu\text{s}$  and  $W = 0.325$ . Equation (5) is used to correctly calculate  $EOT = 1.05$ , and Eq. (8) is used to correctly calculate  $SCF = 0.913$ , resulting in  $SCF' = 0.959$ . Then  $\tau_{eff} = 4.90 \mu\text{s}$  is determined from the measured photoconductance, using Eqs. (10) and (1). The solution to the continuity equation [6] gives  $S = 3340 \text{ cm/s}$ . If Eq. (3) were used instead of the solution to the continuity equation, we would instead find  $S = 2980 \text{ cm/s}$ , an underestimate, as predicted by Fig. 3. If all three guidelines in this paper were ignored, leaving  $EOT = 0.65$  as a default instead of taking into account the anti-reflection coating, implicitly assuming  $SCF = 1$ , and using Eq. (3) instead of the solution to the continuity equation, we would find  $S = 1910 \text{ cm/s}$ , over 40% lower than the correctly obtained  $S = 3340 \text{ cm/s}$ . These results are summarized and expanded in Table 1.

Parameters influencing determination of $G_{av}$	Resulting $\tau_{eff}$ ( $\mu s$ )	S (cm/s) from approximate Eq. (3)	S (cm/s) calculated from full solution [6]	Remarks
EOT = 0.65, SCF = 1	7.23	1910	2020	Default EOT, default SCF
EOT = 1.05, SCF = 1	4.47	3300	3760	Correct EOT, default SCF
EOT = 0.65, SCF = 0.913	7.92	1720	1800	Default EOT, correct SCF
EOT = 1.05, SCF = 0.913	4.90	2980	<b>3340</b>	Correct EOT, correct SCF

Table 1. Impact of correct determination of EOT and SCF on  $\tau_{eff}$  determined from photoconductance data for a nitride-coated HEM wafer. S is calculated from  $\tau_{eff}$  using either the approximate Eq. (3) or the full solution to the continuity equation for exponentially decaying illumination intensity [6].  $S = 3340$  cm/s is the result of correctly following the three guidelines described in this paper.

## 6. Conclusions

This paper clarifies methods to circumvent three errors that may commonly affect the calculation and interpretation of  $\tau_{eff}$ . The calculation of EOT from measured wafer reflectance and lamp irradiance has been described in this paper and illustrated by examples. The spectral correction factor and its determination are introduced in this paper to generalize the standard data analysis spreadsheet for arbitrary spectra. SCF = 0.913 for the flash lamp as a result of its deviation from the AM1.5 spectrum. While the use of  $SCF' = SCF \times EOT$  permits the accurate calculation of  $\tau_{eff}$ , it must be interpreted correctly: the solution to the time-dependent continuity equation demonstrates that  $1/\tau_{eff} = 1/\tau_b + 2S/W$  underestimates S by more than 25% when  $S > 10000$  cm/s. An example in this paper illustrates that ignoring all three guidelines can cause an error of 40% in S inferred from lifetime data.

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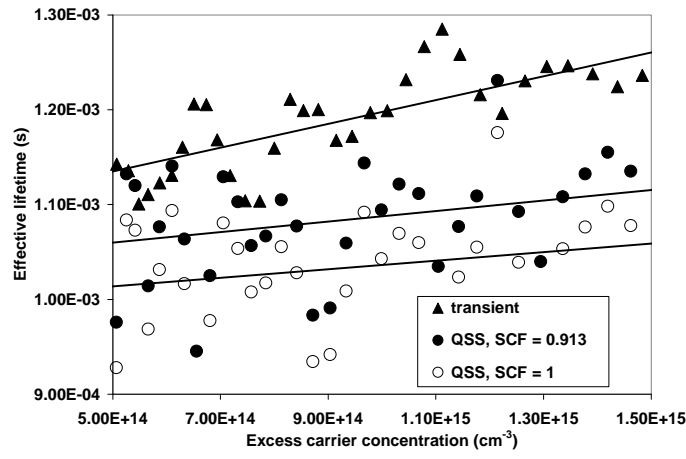


Figure 1. Improvement in the predicted agreement of transient and QSSPC lifetime data upon using  $SCF = 0.913$  calculated by Eq. (8);  $SCF = 1$  indicates that  $SCF$  is neglected.

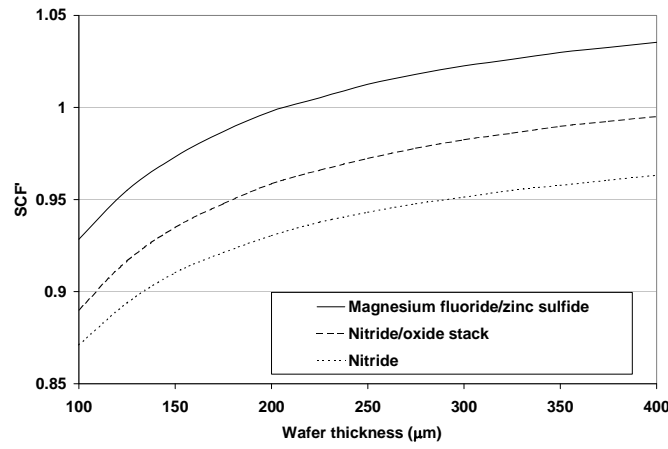


Figure 2.  $SCF'$  calculated using measured wafer reflectance, reference cell EQE, and flash lamp spectral irradiance. The value read off this figure should be used in place of EOT in the data analysis spreadsheet.

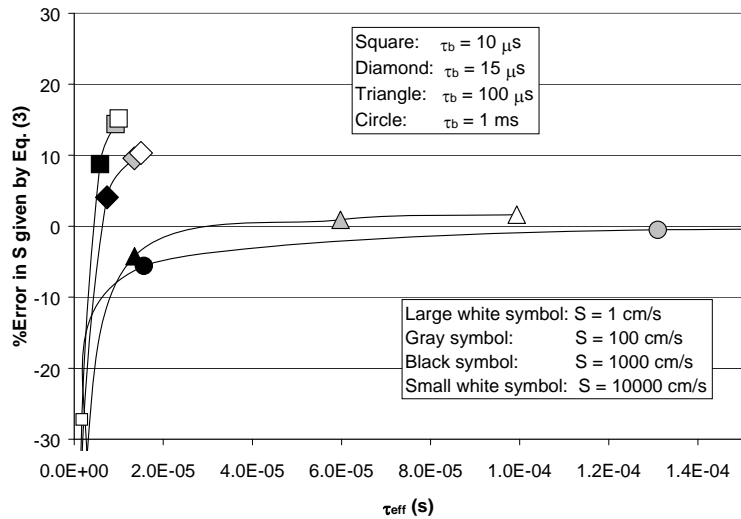


Figure 3. Percentage error in  $S$  given by Eq. (3), compared with actual  $S$  value used in accurate computation of  $\tau_{eff}$  according to [6]. The parameters used include a 2.3 ms lamp time constant,  $N_{ph}(\lambda)$  of the Qflash T2 lamp,  $W = 300 \mu m$ ,  $D = 30 cm^2 s^{-1}$ , and  $t = 2.3 ms$  after the onset of illumination.